Determination of the Θ^+ parity from $\gamma n \to K^- K^+ n$

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Abstract

It is demonstrated that measurements of photon asymmetry in the $\gamma n \to K^- K^+ n$ reaction, can most likely determine the parity of the newly discovered Θ^+ pentaquark. We predict that if the parity of Θ^+ is positive, the photon asymmetry is significantly positive; if the parity is negative, the photon asymmetry is significantly negative. If the background contribution is large, the photon asymmetry may become very small in magnitude, thereby making it difficult to distinguish between the positive and negative parity results. However, even in this case, a combined analysis of the $(K^+ n)$ invariant mass distribution and photon asymmetry should allow a determination of the parity of Θ^+.

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The recent discovery of the pentaquark baryon Θ^+ with the strangeness quantum number $S = +1$, mass $m_{\Theta^+} = 1.54 \pm 0.01 GeV$ and width $\Gamma < 25 MeV$ by the LEPS Collaboration at SPring-8 [1] has triggered an intensive investigation of exotic baryons. The Θ^+ baryon (renamed from Z^+) has been also identified by other experimental groups [2–5]. Furthermore, the NA49 Collaboration [6] has reported the finding of another pentaquark baryon, $\Xi_{3/2}$, with $S = -2$. The pentaquark $\Theta^+(Z^+)$ was predicted by Diakonov, Petrov and Polyakov [7] in 1997 in the chiral soliton model as the lowest member of an anti-decuplet baryons. The existence of such exotic baryons was discussed even earlier by a number of authors [8–10]. Before the announcement of the LEPS Collaboration's discovery, a theoretical study of the $\Theta^+(Z^+)$ was also made based on the Skyrme model [11]. Also, investigation about some experimental possibilities have been made in Ref. [12].

Although the existence of Θ^+ has been confirmed experimentally, many of its basic properties such as its quantum numbers remain undetermined. From the lack of a signal in the (K^+p) invariant mass distribution in $\gamma p \to K^-K^+p$, the SAPHIR Collaboration [4] has concluded that Θ^+ should be an isoscalar state. Currently available data do not allow for the determination of either its spin or its parity. Consequently, many theoretical studies of Θ^+, based on a number of different approaches, are available aimed at establishing these properties [13–28]. The results, however, are largely controversial. Naive SU(6) quark model as well as QCD sum rule [20,22] calculations predict a spin 1/2 negative parity state. Also, recent quenched lattice QCD calculations [23] identified the spin 1/2 Θ^+ as the lowest mass (1539 ± 50 MeV) isoscalar negative parity state; a state with either isospin 1 and/or positive parity lies at a higher mass. In contrast, chiral/Skyrme soliton models [7,11] and correlated quark models [13,15] predict a spin 1/2 positive parity isoscalar state. Goldstone boson exchange [16,19] and color magnetic exchange quark models [19] also predict a positive parity for Θ^+. Yet, in another work [26], the observed narrow width of Θ^+ has been ascribed to this baryon possibly belonging to an isotensor multiplet. Concerning the structure of Θ^+, an interesting possibility of a diquark-diquark-antiquark $([ud][ud]\bar{s})$ flavor structure for Θ^+ has been introduced in Ref. [13] (see also Refs. [18,21]). On the other hand, in Ref. [14] it is interpreted as having a diquark-triquark $([ud][ud\bar{s}])$ structure. In addition to these theoretical efforts, there exists other theoretical studies addressing the reaction aspects involving Θ^+ [29–36]. In particular, Refs. [34–36] explore the possibility of determining its quantum numbers (parity) experimentally. However, none of these calculations have considered the three/four-body final states which are involved in the actual experiments; the Θ^+ baryon is present only in the intermediate state in these experiments.

In the present study we focus on the $\gamma n \to K^-K^+n$ reaction, which has been investigated experimentally by the LEPS Collaboration [1], and demonstrate that measurements of the photon asymmetry in conjunction with (K^+n) invariant mass distribution can most likely determine the parity of an isospin 0 and spin 1/2 Θ^+ pentaquark.

In Fig.1 we depict the processes considered in the present work. In order to investigate the effect of various reaction mechanisms, we group the diagrams (a)-(d) and (a')-(c') together and refer to them as the K contribution. Diagrams (e) and (e') are referred to as the K^* contribution. Together $(K + K^*)$, they constitute the Θ^+ (resonance) contribution. Although experimental evidence [1–5] suggests a strong $NK\Theta^+$ coupling, the $NK^*\Theta^+$ coupling may also be important in the excitation of the Θ^+ [36]. In order to obtain results which can be compared directly to those measured, the background contribution needs to be in-

cluded in the calculation. Presently, however, there is a large uncertainty in the background contribution. We therefore make a rough estimate of its effect relevant for the present study. We consider the ρ, ω and ϕ meson exchange diagrams (Figs.1(f)-(j), (i'), and (j')). In addition, we also include the $\Sigma(1197)^-$ and $\Sigma(1660)^-$ contributions for the background. They are obtained from the diagrams Figs.1(a)-(e) and (a')-(e') by replacing Θ^+ by $\Sigma(1197)^-$, $\Sigma(1660)^-$ and interchanging $K^-(q_1)$ with $K^+(q_2)$. Although the decay channels $\rho \to \bar{K}K$ and $\omega \to \bar{K}K$ are kinematically closed, these vector meson exchanges contribute largely to the background due to their strong coupling to nucleons. The $\Sigma(1197)^-$ is expected to have a strong coupling to the $N\bar{K}$ channel according to the hyperon-nucleon (YN) interaction models [37], and the $\Sigma(1660)^-$ has an appreciable decay branch to the $N\bar{K}$ channel [38]. It is possible to remove the ϕ exchange contribution from the experimental background by measuring the (K^+K^-) invariant mass distribution and rejecting the events corresponding to it (ϕ) as has been done in Refs. [1,3,4,39]. In principle, the $\Sigma(1660)^-$ contribution may also be removed from the experimental background by measuring the (K^-n) invariant mass distribution. However, this may not be practical due to the relatively large width of this resonance.

We work with an effective Lagrangian at the hadronic level. The hadronic parts of the interaction Lagrangian are given by:

$$\mathcal{L}^{\pm}_{NKR} = -g_{NKR}\bar{N}\left[i\lambda\Gamma^{\pm}R \pm \frac{1-\lambda}{m_R \pm m_N}\Gamma^{\pm}_{\mu}R\partial^{\mu}\right]K + h.c., \qquad [R = \Theta^+, \vec{\tau}\cdot\vec{\Sigma}(1197), \vec{\tau}\cdot\vec{\Sigma}(1660)], \tag{1}$$

$$\mathcal{L}^{\pm}_{NK^*R} = \frac{g_{NK^*R}}{(m_R+m_N)^2} \times \bar{N}\left[\Gamma^{\mp}_{\mu}R\partial^2 \mp (m_R \mp m_N)i\Gamma^{\mp}R\partial_{\mu} + (m_R+m_N)\kappa^*\Gamma^{\mp}\sigma_{\mu\nu}R\partial^{\nu}\right]K^{*\mu} + h.c., \qquad [R = \Theta^+, \vec{\tau}\cdot\vec{\Sigma}(1197), \vec{\tau}\cdot\vec{\Sigma}(1660)], \tag{2}$$

$$\text{with} \quad \Gamma^{\pm} = \begin{pmatrix}\gamma_5 \\ 1\end{pmatrix}, \Gamma^{\pm}_{\mu} = \begin{pmatrix}\gamma_5\gamma_{\mu} \\ \gamma_{\mu}\end{pmatrix},$$

$$\mathcal{L}_{VNN} = -g_{VNN}\bar{N}\left\{\left[\gamma_{\mu} - \frac{\kappa_V NN}{2m_N}\sigma_{\mu\nu}\partial^{\nu}\right]V^{\mu}\right\}N, \ \ [V^{\mu} = (\vec{\tau}\cdot\vec{\rho}^{\mu}), \omega^{\mu}, \phi^{\mu}], \tag{3}$$

$$\mathcal{L}_{VKK} = -ig_{VKK}\left[\bar{K}V^{\mu}(\partial^{\mu}K) - (\partial_{\mu}\bar{K})V^{\mu}K\right], \ \ [V^{\mu} = (\vec{\tau}\cdot\vec{\rho}^{\mu}), \omega^{\mu}, \phi^{\mu}], \tag{4}$$

where $K^T = (K^+, K^0)$ and $\bar{K} = (K^-, \bar{K}^0)$ and similarly for $(K^{*\mu})^T$ and $\bar{K}^{*\mu}$, with T the transpose operation. The superscript $\pm$ in Eqs.(1,2) as well as in Eq.(7) below stands for the positive (+) and negative (−) parity baryon R. The parameter λ appearing in Eq.(1) controls the pseudoscalar-pseudovector (ps-pv) [scalar-vector] admixture of the KNR coupling for the positive [negative] parity baryon R.

In addition, the electromagnetic parts of the interaction Lagrangian are given by:

$$\mathcal{L}_{BB\gamma} = -\bar{B}e_B\left\{\left[\gamma_{\mu} - \frac{\kappa_B}{2m_N}\sigma_{\mu\nu}\partial^{\nu}\right]A^{\mu}\right\}B, \ \ [B = \Theta^+, N, \Sigma(1197)^-, \Sigma(1660)^-], \tag{5}$$

$$\mathcal{L}_{KK\gamma} = -ie\left[K^-(\partial_{\mu}K^+) - (\partial_{\mu}K^-)K^+\right]A^{\mu}, \tag{6}$$

$$\mathcal{L}^{\pm}_{NKR\gamma} = \mp ieg_{NKR}\left(\frac{1-\lambda}{m_R \pm m_N}\right)\bar{R}\Gamma^{\pm}_{\mu}NK^-A^{\mu} + h.c., \ \ [R = \Theta^+, \Sigma(1197)^-, \Sigma(1660)^-], \tag{7}$$

$$\mathcal{L}_{KK^*\gamma} = \left(\frac{g_{KK^*\gamma}}{m_K}\right)\varepsilon^{\mu\nu\lambda\sigma}(\partial_\mu A_\nu)\left[(\partial_\lambda K^-)K_\sigma^{*+} + (\partial_\lambda \bar{K}^0)K_\sigma^{*0}\right] + h.c., \tag{8}$$

$$\mathcal{L}_{\rho\rho\gamma} = -e\left\{A^\mu[\vec{\rho}^\nu \times (\partial_\mu\vec{\rho}_\nu - \partial_\nu\vec{\rho}_\mu)]_3 - (\partial^\mu A^\nu)[\vec{\rho}_\mu \times \vec{\rho}_\nu]_3\right\}, \tag{9}$$

$$\mathcal{L}_{\rho NN\gamma} = e\frac{f_{\rho NN}}{2m_N}\bar{N}\sigma_{\mu\nu}A^\mu(\vec{\rho}^\nu \times \vec{\tau})_3 N \tag{10}$$

$$\mathcal{L}_{VKK\gamma} = eg_{VKK}K^-K^+V^\mu A_\mu + h.c., \ \ [V^\mu = \rho_3^\mu, \omega^\mu, \phi^\mu], \tag{11}$$

where e_B in Eq.(5) is the electric charge operator of the baryon B and, e, the proton charge. A^μ stands for the photon field. Note that the same parameter λ in Eq.(1) also appears in Eq.(7). This is needed to ensure gauge invariance of the resulting reaction amplitude. The same is true for the coupling constant $f_{\rho NN} \equiv g_{\rho NN}\kappa_\rho$ in Eqs.(3,10).

The values of the coupling constants in the above interaction Lagrangians are summarized in Table I. We utilize the relevant sources whenever available as indicated in the Table to determine these couplings. Most of those couplings that cannot be extracted from other sources, are estimated following Ref. [40] from a systematic analysis based on SU(3) symmetry in conjunction with Okubo-Zweik-Iizuka (OZI) rule constraints [41] and some experimental data. The remaining few parameter values are simply assumed. The coupling constant $g_{NK\Theta}$ in Eq.(1) is estimated using the upper limit of the decay width of $\Gamma_{(\Theta^+\to K^+n)} = 25MeV$ [1]. The mixing parameter λ in Eq.(1) is treated as a free parameter; we consider both the extreme values of $\lambda = 1$ and $\lambda = 0$. Nothing is known about the coupling constant $g_{NK^*\Theta}$ in Eq.(2). Following Ref. [36] we employ $g_{NK^*\Theta} \sim (1/2)g_{NK\Theta}$, assuming the same ratios obtained for the NKY to NK^*Y coupling constants ($Y = \Sigma, \Lambda$) empirically [42]. We also consider $g_{NK^*\Theta} \sim -g_{NK\Theta}$, an estimate resulting from assuming the same ratio obtained for the $NK\Sigma$ to $NK^*\Sigma$ coupling constants from SU(3) symmetry considerations (see Table I). Furthermore, both choices of the sign ($\pm$) for $g_{NK^*\Theta}$ are also considered. The tensor to vector coupling constant ratio κ^* in Eq.(2) is treated as a free parameter; we consider $\kappa^* = -3, 0, +3$. In Table I, for the D to F admixture parameter $\beta = (D/F)/[1 + (D/F)]$ in the SU(3) baryon-baryon-pseudoscalar meson Lagrangian [40], we use the value of $\beta \simeq 0.63$ [43] as obtained from averaging the values extracted from a systematic analysis of semileptonic hyperon decays [44]. In the baryon-baryon-vector meson Lagrangian we take $\beta = 0$ [40] which is a consequence of requiring spin independence for $BB\omega$ and $BB\phi$ couplings within the identically flavored baryons ($B = \Lambda, \Sigma$). For further details about the determination of the coupling constants, we refer to Ref. [40].

It should be stressed that the present calculation cannot provide a quantitative prediction of the absolute value of the cross section. In phenomenological approaches like the present one, one usually introduces form factors at the hadronic vertices to account for the composite nature of hadrons. It happens that little is known about the form factors needed in the present study, and the introduction of such form factors would significantly increase the number of unknown parameters in the model. Moreover, the presence of form factors usually leads to the breaking of gauge invariance of the resulting amplitude and a proper restoration of gauge invariance is not a trivial task. Therefore, in the present study, we simply leave out the form factors. Accordingly, we expect that the present calculation should be more reliable for relative quantities than for absolute cross sections. (In lowest order, the role of form factors would cancel exactly in calculations of relative quantities such as the photon asymmetry if the process were dominated by a single production mechanism. Incidentally, for the (K^+n) invariant mass around the resonance peak, diagram Fig. 1(b) dominates in

the case of a positive parity Θ^+; moreover, this diagram would not be affected much by the (off-shell) form factors, for Θ^+ will be nearly on-shell. As we shall show, for a negative parity Θ^+, the background contribution may be relatively large, in which case the influence of the form factors may be stronger.) A quantitative assessment of this reliability would require exploratory calculations which include a range of (unknown) form factors, in addition to properly preserving gauge invariance of the resulting amplitude. This is beyond the scope of this letter.

The primary focus of this study is on the photon asymmetry. It is defined as follows: let the 4-momenta of the photon and K^- meson be $k^\mu \equiv (|\vec{k}|, 0, 0, |\vec{k}|)$ and $q_1^\mu \equiv (q_1^0, q_{1x}, 0, q_{1z}) = (q_1^0, \vec{q}_1)$, respectively. Take the y-axis parallel to $(\vec{k} \times \vec{q}_1)$ and define the photon polarization vectors, $\epsilon^\mu(\lambda_\gamma = +1) \equiv (0, 0, 1, 0)$ and $\epsilon^\mu(\lambda_\gamma = -1) \equiv (0, 1, 0, 0)$. Then, the photon asymmetry, Σ, is given by,

$$\Sigma \equiv \frac{d\sigma(\lambda_\gamma = +1) - d\sigma(\lambda_\gamma = -1)}{d\sigma(\lambda_\gamma = +1) + d\sigma(\lambda_\gamma = -1)}, \tag{12}$$

where $d\sigma(\lambda_\gamma) \equiv d^2\sigma(\lambda_\gamma)/[dm_{(K^+n)} d\Omega_{K^-}]$ with $m_{(K^+n)}$ being the invariant mass of the (K^+n) system.

We now focus on the results of the present calculation. Let's first concentrate on the K contribution. Fig.2 shows the results for the (double differential) cross sections (upper figure) and photon asymmetries (lower figure) as a function of K^- emission angle, $\cos(\theta_{K^-})$, in the overall center-of-mass (c.m.) frame at an incident photon laboratory energy of $T_\gamma = 2$ GeV and fixed (K^+n) invariant mass $m_{(K^+n)} = 1.54$ GeV. Results are shown for both the positive ($J^P = 1/2^+$) and negative ($J^P = 1/2^-$) parity choices of Θ^+. Different curves correspond to different values of the ps-pv (scalar-vector) mixing parameter λ in Eq.(1) and the anomalous magnetic moment κ_Θ of Θ^+ in Eq.(5). These are the only free parameters in the K contribution. As can be seen, for the cross section, the case of positive parity Θ^+ (upper panel) enhances the angular distribution at forward angles as the anomalous magnetic moment κ_Θ decreases. For the negative parity case (lower panel), however, the effect of κ_Θ is just the opposite, i.e., the angular distribution is reduced at forward angles as κ_Θ decreases. A comparison of the solid ($\lambda = 0$) and dotted ($\lambda = 1$) curves reveals the sensitivity of the angular distribution to the ps-pv (scalar-vector) mixing parameter λ. For the positive parity case, it is quite insensitive to this parameter, while for the negative parity case, the cross section is enhanced primarily at backward angles. Apart from the fact that the cross section is much smaller for the negative parity case of Θ^+ than for the positive parity case - a feature that has been also pointed out in Ref. [36] - one can conclude that it will be difficult to determine the parity of Θ^+ from the shape of the angular distribution. However, the situation is quite different for the photon asymmetry Σ. The lower figure in Fig.2 illustrates the sensitivity of the photon asymmetry Σ to the only free parameters, λ and κ_Θ, of the calculation. One can see that for the positive parity case of Θ^+ the photon asymmetry Σ is always positive, while it is always negative for the negative parity case. Therefore, in contrast to the cross section, measurements of the photon asymmetry Σ can potentially determine the parity of Θ^+. Of course, other reaction mechanism(s) should be investigated before a more definitive statement can be made, and we now examine this.

Fig.3 illustrates the results when the K and K^* contributions $(K + K^*)$ are included. Here, we show the results for fixed parameter values of $\lambda = 0$ and $\kappa_\Theta = 0$ in the K

contribution. Other choices of these parameters (as in Fig.2) lead to the same qualitative conclusion and therefore we do not show the corresponding results here. The K^* contribution introduces two new parameters: the $NK^*\Theta$ coupling constant $g_{NK^*\Theta}$, and the value of the tensor to vector coupling constant ratio κ^* in Eq.(2). We consider the values as given in Table I, in addition to both choices of the sign ($\pm$) for $g_{NK^*\Theta}$. As one can see, both the cross section and photon asymmetry are rather insensitive to the values of κ^*. However, they are sensitive to the sign of the coupling constant $g_{NK^*\Theta}$. For the cross section (upper figure), the angular distribution changes from a strongly forward peaked (solid curve) to a flat (dashed curve) shape as the coupling constant changes from $g_{NK^*\Theta} = +2.45$ to $g_{NK^*\Theta} = -2.45$. Doubling the value of $g_{NK^*\Theta}$ (short-dashed curve) does not affect either the magnitude or the shape of the angular distribution significantly. For the negative parity case of Θ^+ (lower panel), the effect of the sign of the $NK^*\Theta$ coupling constant, $g_{NK^*\Theta} = \pm 0.34$, is not as strong as that for the positive parity case. Also, doubling the coupling constant value shows no significant effect. The corresponding results for the photon asymmetry Σ is shown in the lower figure in Fig.3. For this observable the difference between the positive and negative parity cases is dramatic over the entire range of the K^- emission angle. The photon asymmetry Σ also shows a significant sensitivity to the magnitude of $g_{NK^*\Theta}$. In any case, as in Fig.2, the photon asymmetry is always positive for the positive parity choice of Θ^+, while it is always negative for the negative parity choice. Thus, if K^* contributes to the Θ^+ excitation at all, it enhances the difference in the photon asymmetries between the positive and negative choices of the Θ^+ parity.

We now consider the background contribution. First of all, as mentioned before, this contribution is largely uncertain theoretically, mainly due to many unknown coupling parameters including form factors. Some of the background contributions can be removed experimentally, by rejecting events associated with them which can be identified from appropriate invariant/missing mass distributions [1,3,4,39]. Keeping these facts in mind, we make a rough estimate of the background effects in the present approach. We consider the background consisting of the $\Sigma(1197)^-$ and $\Sigma(1660)^-$ intermediate states as well as the ρ, ω and ϕ exchange contributions. The results are shown in Fig.4. First we examine the photon asymmetry (upper figure). The dashed curves correspond to the results including the background contribution, while the solid curves correspond to the results without it. The latter are the same results shown as solid curves in Fig.3. For the positive parity choice for Θ^+, the background only weakly affects the photon asymmetry. This is because the $K + K^*$ contribution is much larger than the background. For the negative parity case, however, the background contribution is relatively large and affects the photon asymmetry significantly. In particular, this observable becomes small in magnitude, even changing its sign at backward angles when compared to the results without the background. This makes it difficult to distinguish it from the positive parity choice. (The wiggles shown are due to the pole structure of the ϕ meson exchange. In the present calculation, we have taken the widths of the exchanged vector mesons as given in Ref. [38] into account.) The results corresponding to other choices of the parameters considered in the present work are not different qualitatively from those shown in Fig.4. Of course, how much the background will affect the resulting photon asymmetry depends on how large or how small it is compared to the $K + K^*$ (Θ^+ excitation) contribution. Therefore, it is crucial to be able to make a reliable estimate of the background relative to the $K + K^*$ contribution if we are to determine the

parity of Θ^+ from photon asymmetry. Here, we show that a measurement of the (K^+n) invariant mass distribution can be used to cross check the background contribution. In the lower figure in Fig. 4 the result for the (K^+n) invariant mass distribution is shown. The dashed curves correspond to the $K + K^*$ contribution alone. The dotted curves correspond to the vector meson exchange contributions due to the ρ, ω and ϕ mesons; the dash-dotted curves correspond to the $\Sigma(1197)^- + \Sigma(1660)^-$ contribution. The solid curves denote the total contribution. As can be seen, the background is dominated by the exchange of vector mesons. For the case of positive parity Θ^+ the peak-to-background ratio is large (~ 10), and the peak structure due to Θ^+ is very clear. In contrast, for the negative parity choice this ratio is relatively small (~ 1.4) and the peak structure due to Θ^+ is not pronounced as for the positive parity case. This is due to the fact that the $K + K^*$ contribution to the cross section is suppressed to a large extent in the case of a negative parity Θ^+ compared to a positive parity Θ^+. This result illustrates that, even if the measured photon asymmetry is small in magnitude (which means a significant background contribution), one can still learn about the parity of Θ^+ by cross checking the peak-to-background ratio in the (K^+n) invariant mass distribution. Thus, a combined analysis of the (K^+n) invariant mass distribution and the photon asymmetry should be able to fix the parity of Θ^+. (Of course, measurement of the signal/noise ratio depends sensitively on the width of the Θ^+ baryon.)

In summary, we have demonstrated that measurements of photon asymmetry as a function of K^- emission angle in the $\gamma n \to K^- K^+ n$ reaction, can most likely determine the parity of the newly discovered Θ^+ pentaquark. We predict that if the parity of Θ^+ is positive, the photon asymmetry is significantly positive; if the parity is negative, the photon asymmetry is significantly negative. It is possible that the photon asymmetry can be affected considerably if the background contribution is relatively large. Unfortunately, at present, the background contribution is not well understood theoretically. In particular, for the negative parity case, the photon asymmetry may become very small in magnitude, even changing its sign depending on the K^- emission angle. However, even in this worst case scenario, a combined analysis of the (K^+n) invariant mass distribution and photon asymmetry should allow a determination of the parity of Θ^+.

After the completion of this work, a preprint by Q. Zhao and J. S. Al-Khalili [hep-ph/0310350] came to our attention which explores the sensitivity of the photon asymmetry to the parity of Θ^+ in the $\gamma n \to K^- \Theta^+$ reaction. Their finding is consistent with the present results.

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TABLES

TABLE I. SU(3) relations among the coupling constants, values and types for the coupling constants used in the calculation.

Coupling constant	Sources
$g_{NK\Theta} = 4.9,\ \ \lambda = (0,1) =$(pv,ps)	$J^p = (1/2)^+, \Gamma_{(\Theta^+ \to NK)} = 25$ MeV Ref. [1]
$g_{NK\Theta} = 0.7,\ \ \lambda = (0,1) =$(vector,scalar)	$J^p = (1/2)^-, \Gamma_{(\Theta^+ \to NK)} = 25$ MeV Ref. [1]
$g_{NK^*\Theta} = -g_{NK\Theta}, (1/2)g_{NK\Theta},\ \ \kappa^* = -3, 0, 3$	SU(3)/empirical g_{NK^*Y}/g_{NKY} $(Y = \Sigma, \Lambda)$
$g_{NK\Sigma(1197)} = -g_{\pi NN}(1-2\beta) = 3.6,\ \lambda = 0$	SU(3) + OZI ($\beta \simeq 0.63$) [43,44]
$g_{NK^*\Sigma(1197)} = -g_{\rho NN}(1-2\beta) = -3.36$	SU(3) + OZI ($\beta = 0$) [40]
$\kappa_{NK^*\Sigma(1197)} = 0$	Assumption
$g_{NK\Sigma(1660)} = 2.6$	$g_{NK\Sigma(1660)} > 0$ assumption, $\Gamma_{(\Sigma(1660) \to N\bar{K})}$ PDG [38]
$\kappa_{NK^*\Sigma(1660)} = 0$	Assumption
$g_{\rho NN} = 3.36,\ \ \kappa_\rho = 6.1$	Bonn Potential [45]
$g_{\omega NN} = 9.0,\ \ \kappa_\omega = 0$	SU(3)+OZI [40,46]
$g_{\phi NN} = -0.65,\ \ \kappa_\phi = 0$	SU(3)+OZI [40,46]
$g_{\phi KK} = \frac{1}{2}(\sqrt{2}\cos\alpha_V - \sin\alpha_V)g = 4.5$	SU(3)+OZI [40], $\Gamma_{(\phi \to K^+K^-)}$ PDG [38]
$g_{\omega KK} = \frac{1}{2}(\cos\alpha_V - \sqrt{2}\sin\alpha_V)g = 3.7$	$\alpha_V \simeq 3.8^\circ$ [40,43]
$g_{\rho KK} = \frac{1}{2}g = 3.4$	$g > 0$ from Vector Meson Dominance
$\kappa_{\Theta^+} = -1.8, 0, 1.8$	
$\kappa_{\Sigma(1197)^-} = -1.16$	PDG [38]
$\kappa_{\Sigma(1660)^-} = \kappa_{\Sigma(1197)^-}$	Assumption
$g_{K^\pm K^{*\pm}\gamma} = 0.47e = 0.14$	SU(3)+OZI [40], $\Gamma_{(K^{*\pm} \to K^\pm\gamma)}$ PDG [38]

FIGURES

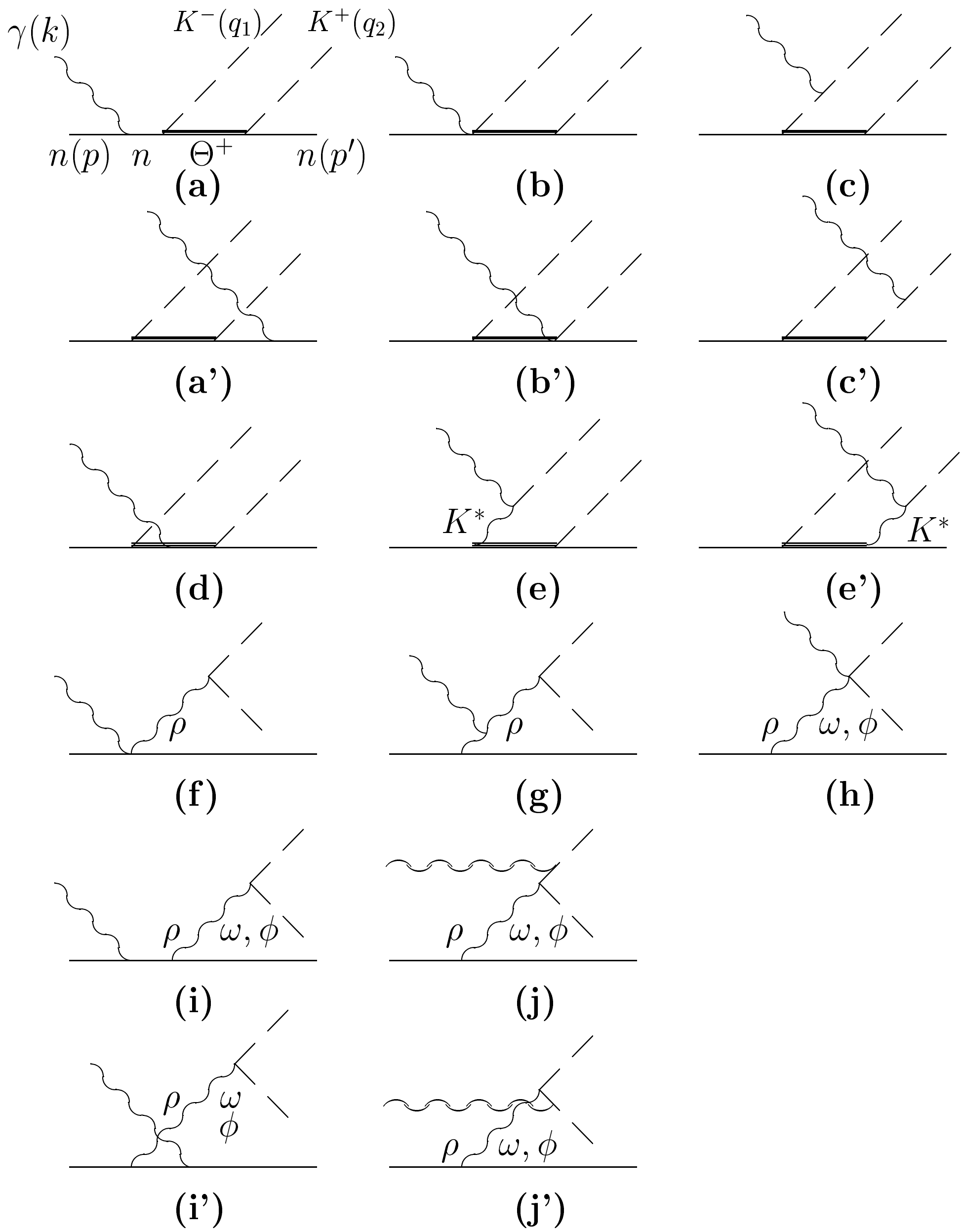

FIG. 1. Processes considered in this study: K [(a)-(d) and (a')-(c')] and K^* [(e) and (e')] contributions, and the background due to the ρ [(f)-(j), (i') and (j')], ω and ϕ [(h)-(j), (i') and (j')] exchanges, and the $\Sigma(1197)^-$ and $\Sigma(1660)^-$ intermediate states [by the replacements, $\Theta^+ \rightarrow \Sigma(1197)^-$ or $\Sigma(1660)^-, K^- \leftrightarrow K^+$ in (a)-(e) and (a')-(e')].

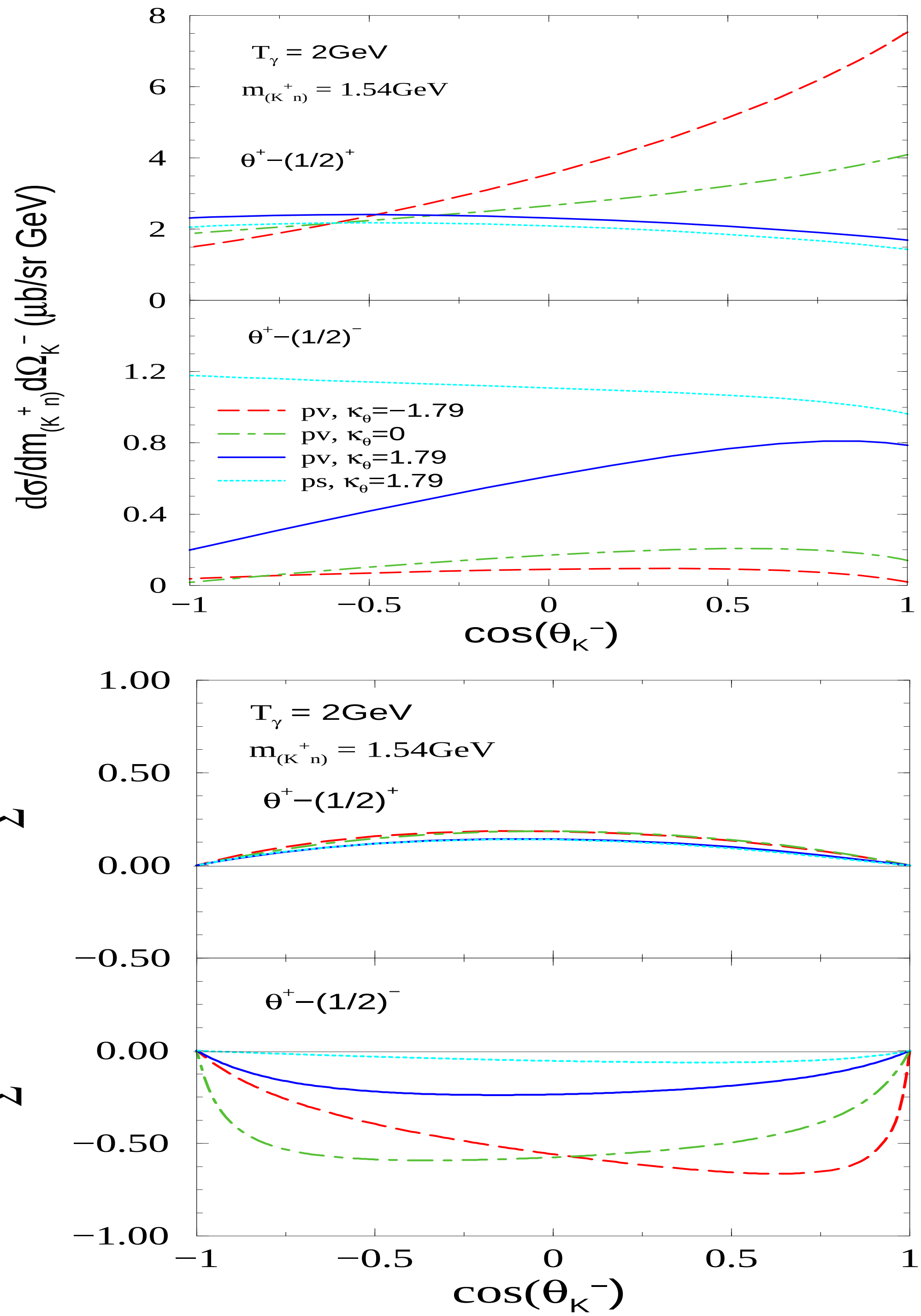

FIG. 2. K^- angular distribution for double differential cross section (upper figure) and photon asymmetry Σ (lower figure) in the (γn) center-of-mass frame calculated with the K contribution alone as defined in the text, for both positive and negative parity cases of Θ^+. The photon laboratory energy is $T_\gamma = 2$ GeV and the (K^+n) invariant mass is $m_{(K^+n)} = 1.54$ GeV. Different curves correspond to different choices of the parameter values λ and κ_Θ in Eqs. (1) and (5), respectively.

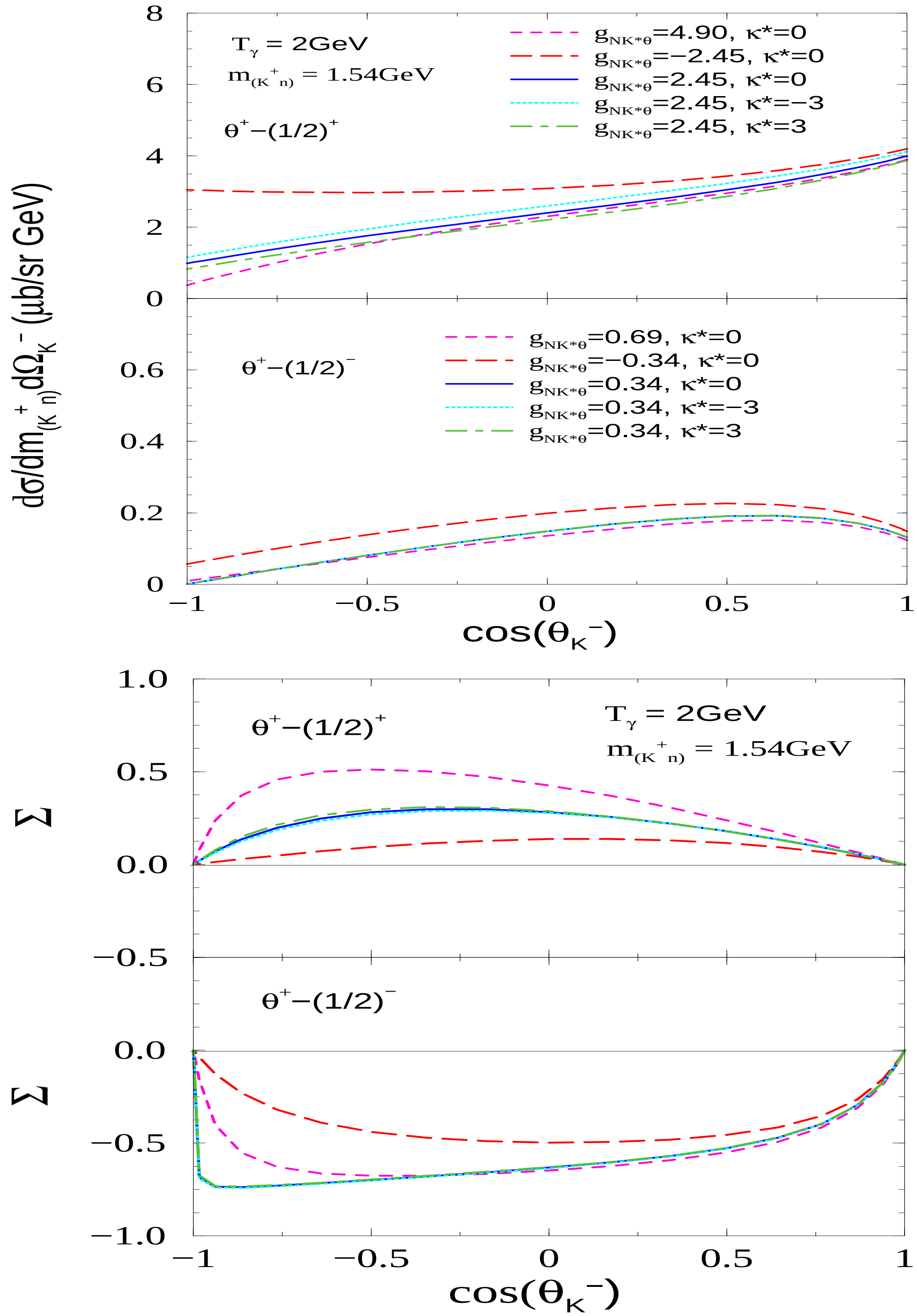

FIG. 3. The same as Fig. 2 but with the $K + K^*$ contribution as defined in the text, and for some values of $g_{NK^*\Theta}$ and the tensor to vector coupling ratio κ^* in Eq.(2).

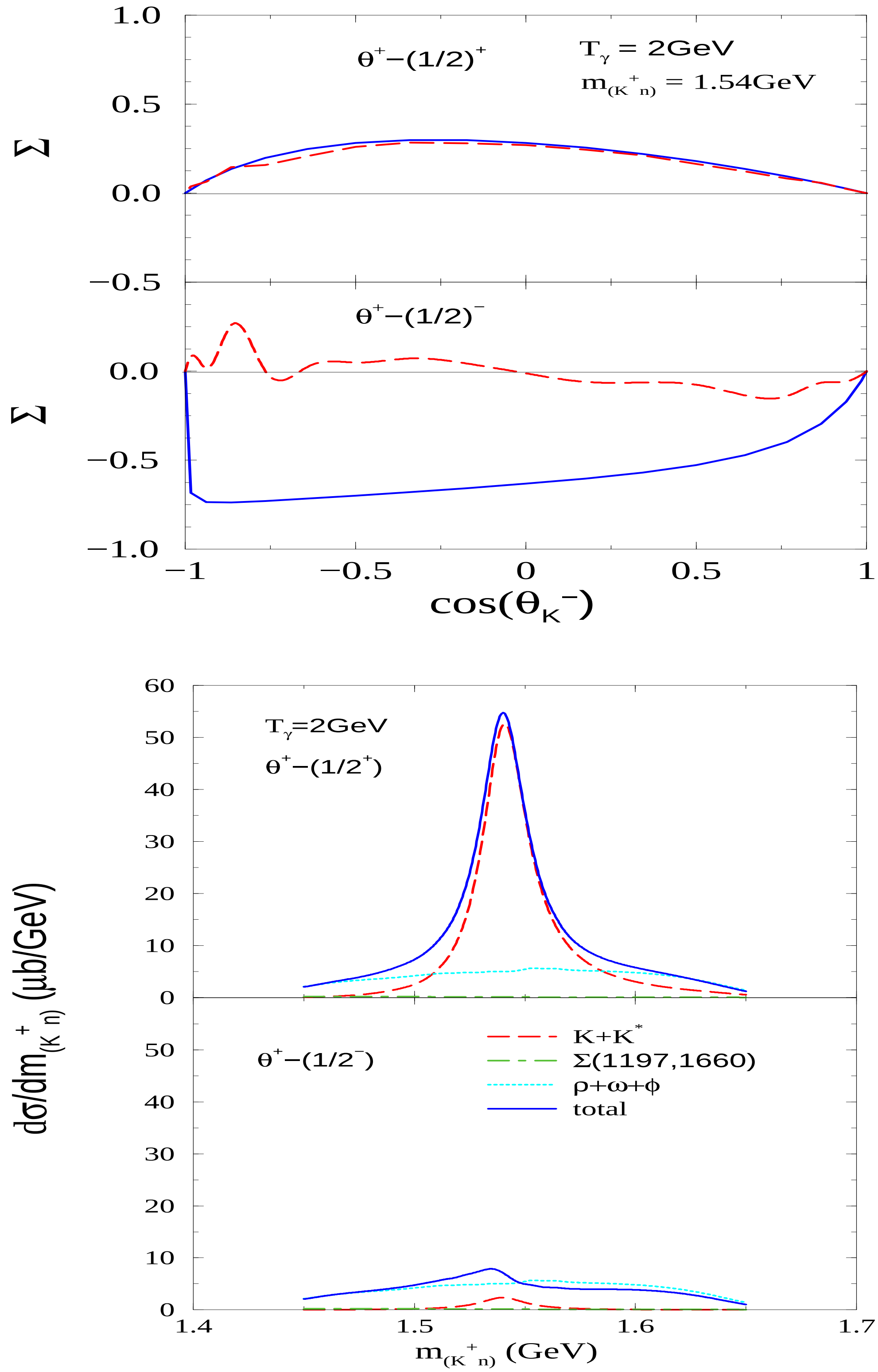

FIG. 4. Upper figure: Photon asymmetry due to the $K + K^*$ contribution alone (solid line) and when the background is included (dashed line) due to the ρ, ω and ϕ exchanges and $\Sigma(1197)^-$ and $\Sigma(1660)^-$ intermediate states. Lower figure: (K^+n) invariant mass distribution. $K + K^*$ contribution alone (dashed curves); ρ, ω and ϕ exchange contribution (dotted curves); $\Sigma(1197)^-$ and $\Sigma(1660)^-$ contribution (dash-dotted curves). The solid curves correspond to the total contribution ($K + K^*$ + background).